THE PREDICTED AND OBSERVED THERMAL PERFORMANCE OF THE BRIGHTON 'EARTHSHIP'

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Summary

This paper reports the findings of initial investigations into the predicted and measured thermal performance of the Brighton 'Earthship', an autonomous earth-sheltered building currently in the late stages of construction in Stanmer Park, Brighton, UK. 'Earthship' design as a form of sustainable building has evolved over the last twenty five years in New Mexico, USA yet this is the first project within England.

Equipment to measure the internal and external conditions contributing to the thermal performance of the 'Earthship' has been installed and recording data since early November 2004. The methodology of extensive long term modelling / measurement programme being undertaken by staff at the University of Brighton Centre for Sustainability of the Built Environment is described within this paper and the preliminary data is analysed and discussed in conjunction with predictive simulations of IES Virtual Environment 5.2.0 (IESVE) software.

There is a need to develop specialist software in order to represent more accurately the novel characteristics of the 'Earthship'. Initial results suggest that minor changes could refine the performance of 'Earthships' in the UK climate. Comparison of simulated with measured data show a good correlation overall, although monitored internal temperatures at the Brighton project exceed the simulated figures.

1.0 Introduction

With accelerating implementation of global and national policies and agendas on reducing the uncertain effects of predicted climate change there has been an increasing recognition of the contribution that the built environment has to this challenge. Approximately 50% of all greenhouse gas emissions (UK figures) are related to the construction, operation and occupation of buildings both commercial and domestic (Harman & Benjamin 2004) and with 26% of the end use of all electricity generation as space heating for these buildings (DTI 2003) their thermal performance is one of the most significant areas in this field for investigation.

The use of earth to shelter buildings is not a new solution. Indeed it has been used for centuries for a number of reasons, for example; defence, camouflage and protection against fires and in response to high population densities (Silber 1991). Over the last 25-30 years the benefits of earth-sheltering to influence thermal performance thereby reducing space heating demands and CO_2 emissions (Littlewood & Geens 2001) in response to economic and environmental energy consumption has become one of the main factors for the development of this type of construction.

1.1 'Earthship' Evolution

One particular type of building which has heavily incorporated earth-sheltering into its ethos is a design known as an 'Earthship', which has been developed and pioneered by US architect / 'biotect' Michael Reynolds. Reynolds has been refining these designs since the early 1970's, largely in Taos, New Mexico, where many buildings of varying design and specification have been completed. 'Earthships' are so named as the concept centres on them being *'independent vessels'* (Reynolds 1990) which operate on a self sufficient basis and are constructed largely from recycled and reclaimed materials. The ethos of 'Earthships' includes; utilisation of low embodied energy materials, passive solar heating and cooling, photovoltaic power systems, rainwater harvesting, solar hot water heating along with black and grey water treatment systems (Earthship Biotecture 2005).

1.2 Glass and Mass

The phrase ‘glass and mass’ is widely used by proponents of ‘Earthships’ to describe the main design principle influencing thermal performance characteristics. Figure 1 depicts this principle showing the maximisation of the winter sun angles and minimisation in the summer through the glazed solar façade.

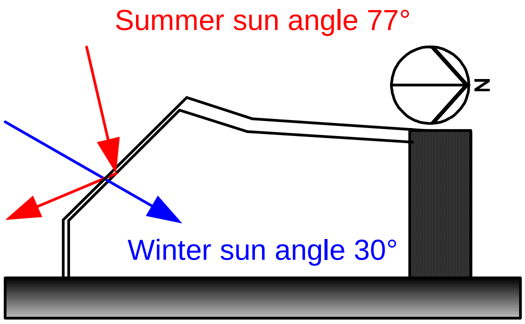


Figure 1 Schematic of solar gain to ‘Earthship’ *Figure 2 Tyre wall undergoing sensor installation*

Thermally massive, earth-sheltered, rear walls (ESRW) are constructed of vertically stacked layers of reclaimed vehicle tyres. These are rammed with earth and precede a layer of pure compacted earth (up to a depth of 1.5 metres) before a plastic barrier and finally the undisturbed earth behind. In practice gaps left because of the circular shape of the tyres have been in filled with other end of useful life materials such as aluminium cans or bottles.

In the UK earth temperatures below the surface become constant at the frost line to between 11and 13°C (Action Renewables 2005). However, nearer the surface temperatures are less stable, being influenced by solar radiation and local factors influencing heat exchanges. The important factor, whichever thermal soil zone forms part of the earth sheltering of a building is that the temperatures are more stable than diurnal cycles thus allowing it to act as a heat source to warm the internal environment in winter and a heat sink to provide cooling in summer (Givoni & Katz 1985, Reynolds, 1990, 2000).

The design of an ‘Earthship’ utilises the tyre wall to act as a thermal battery (Reynolds 1990, Reardon et al 2005). A relationship between the south facing solar gains and the thermal storage properties of the rear wall structure is exploited. The desired effect of regulating of internal temperature fluctuations in relation to the influence of external temperature cycling which is allowed by thermally massive structures, (Goodhew & Griffiths 2005) is the aspect of ‘Earthship’ thermal performance examined within this paper.

1.3 The Brighton ‘Earthship’

‘Earthships’ have, until relatively recently been constructed exclusively in Taos, New Mexico, with the exception of some demonstration projects in other countries. The Brighton Low Carbon Network, responsible for the construction of the Brighton ‘Earthship’, was formed after a talk given by Mike Reynolds, in April 2000 in Brighton. Funding and planning permission allowed work to begin in Stanmer Park, on land owned by Brighton and Hove City Council in July 2002. Initial training for the construction was provided by the American construction team.

The external envelope of the shell is complete and the next stage of internal finishes and installation of the renewable services is ongoing. The International ‘Earthship’ Summit, hosted at the University of Brighton allowed the American team another opportunity to visit the project and advise on completion.

The Brighton ‘Earthship’ is essentially made up of three main rooms, the conservatory and the main living area including kitchen and bathroom internal partitions, usually referred to as the ‘nest’, and the hut which provides additional living accommodation. These are shown in Figure 3 overleaf.

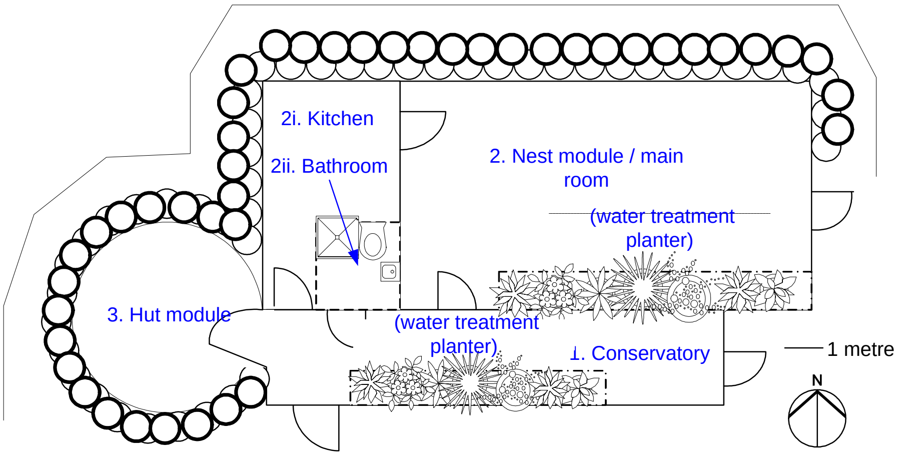


Figure 3   Plan of 'Earthship'

2. Measurement Methodology

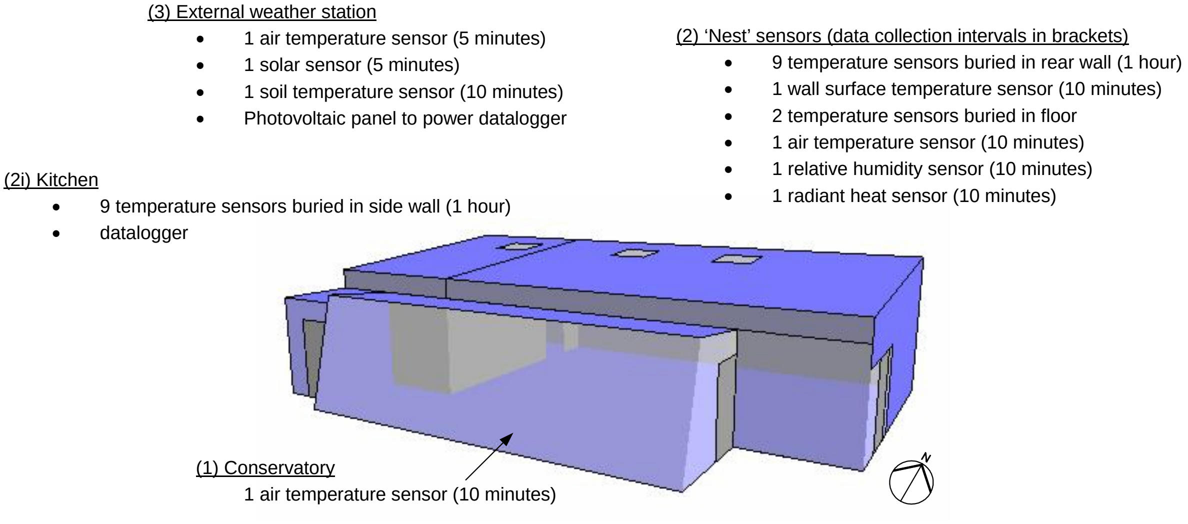
The opportunity for monitoring the Brighton 'Earthship' was presented in April 2003 by the Low Carbon Network, when the majority of the structure was complete. The methodology for monitoring this unconventional building type was devised around two main complementary activities; monitoring temperatures within the thermal mass and monitoring of internal rooms and external climate conditions.

Anecdotal evidence points to the conclusion that the thermal battery effect of the tyre wall takes two years to reach stability and maximum effectiveness. One of the objectives of the University of Brighton research has been to gather empirical data to investigate these beliefs.

Previous monitoring of 'Earthship' thermal behaviour through monitoring of this type in other 'Earthships' has not been extensive. A study by Grindley & Hutchinson (1996) actively monitoring the internal surface, air and mean radiant temperature, along with external air temperature and insolation in order to calibrate a computer simulation in Tas® appears to be the only published results. However, these data were gathered on a limited number of days and did not look at the internal behaviour of the ESRW thermal mass.

In the Brighton 'Earthship' temperature sensors were installed to monitor temperatures within the tyre walls. A total of nine sensors at different depths and heights have been installed to gain a 'thermal grid' of the response of the ESRW thermal mass. This will be the first long term monitoring of the thermal store within 'Earthship' design.

Figure 4 illustrates the model of the conservatory and nest together with an indication of the sensors installed.



(3) External weather station

- 1 air temperature sensor (5 minutes)
- 1 solar sensor (5 minutes)
- 1 soil temperature sensor (10 minutes)
- Photovoltaic panel to power datalogger

(2) 'Nest' sensors (data collection intervals in brackets)

- 9 temperature sensors buried in rear wall (1 hour)
- 1 wall surface temperature sensor (10 minutes)
- 2 temperature sensors buried in floor
- 1 air temperature sensor (10 minutes)
- 1 relative humidity sensor (10 minutes)
- 1 radiant heat sensor (10 minutes)

(2i) Kitchen

- 9 temperature sensors buried in side wall (1 hour)
- datalogger

(1) Conservatory

1 air temperature sensor (10 minutes)

Figure 4   IESVE model of 'Earthship' showing sensor location and details of data collection intervals

3. Monitored Results

At the time of writing monitoring has been completed for a fraction of a heating season and therefore the results should not be considered as representative of inhabited ‘Earthships’. The results are however very important in understanding the thermal performance of the ‘Earthship’ and in developing the techniques to establish computer simulation of the system.

3.1 Internal and External Temperatures

Initial results from the month of December 2004 demonstrate the thermal performance of the ‘Earthship’ and the relative stability of the inside temperature where no traditional space heating is provided (under external conditions that varied between -2.5^{o}C and 12.5^{o}C). Clearly the internal temperatures have not reached suitable conditions for comfort within a dwelling, but at this stage there were no occupants in this building and no internal gains.

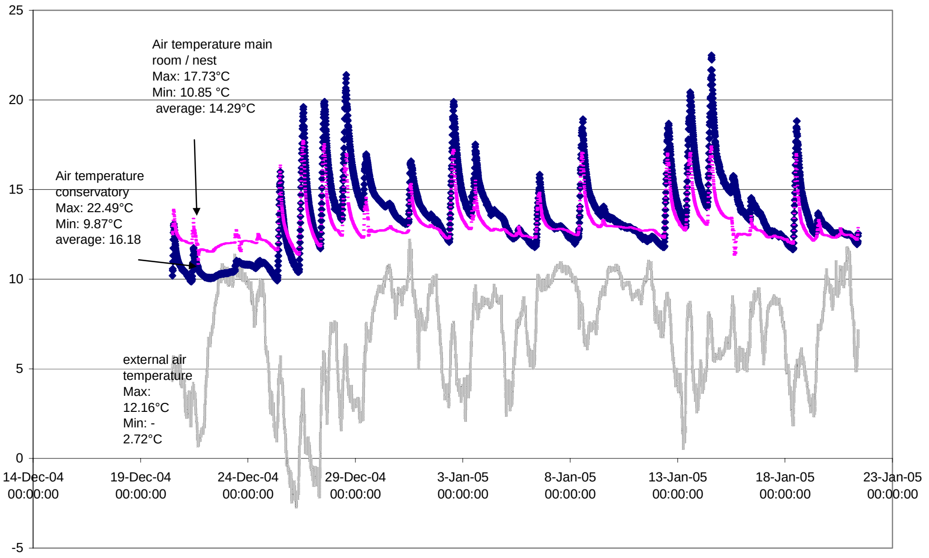


Figure 5 Recorded data for internal and external air temperature

3.2 Temperatures in the Tyre Wall

The temperature in the earth sheltered rear wall in the ‘nest’ module recorded over December 2004 from the 9 probe grid of sensors is an average of 14.8°C.

To look at the profile of the ESRW of the Brighton ‘Earthship’ in more detail Figure 6 marks a clear increase of temperature both with depth horizontally into the mass from the wall surface and with vertical depth into the mass from the external ground surface level (the same level as the ‘Earthship’ roof). This would indicate the correlation expected by the principles of heat storage on which ‘Earthship’ design is based.

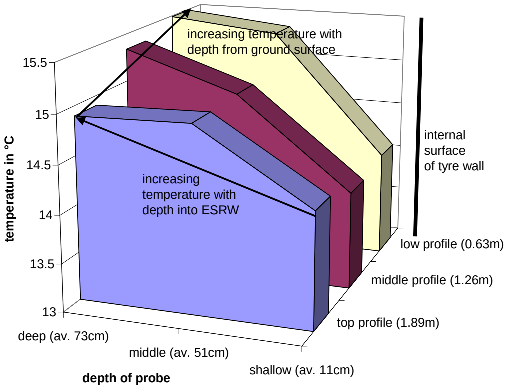


Figure 6 Recorded temperatures for the ESRW in the nest module December 2004

3.3 Impact of Solar Radiation on Internal Temperatures

The correlation between incident solar radiation and internal temperatures in the conservatory area and within the nest are shown in Figure 7. The air temperatures within the building can be seen to respond positively to the incidence of winter sun with the conservatory reaching higher peaks than the nest module.

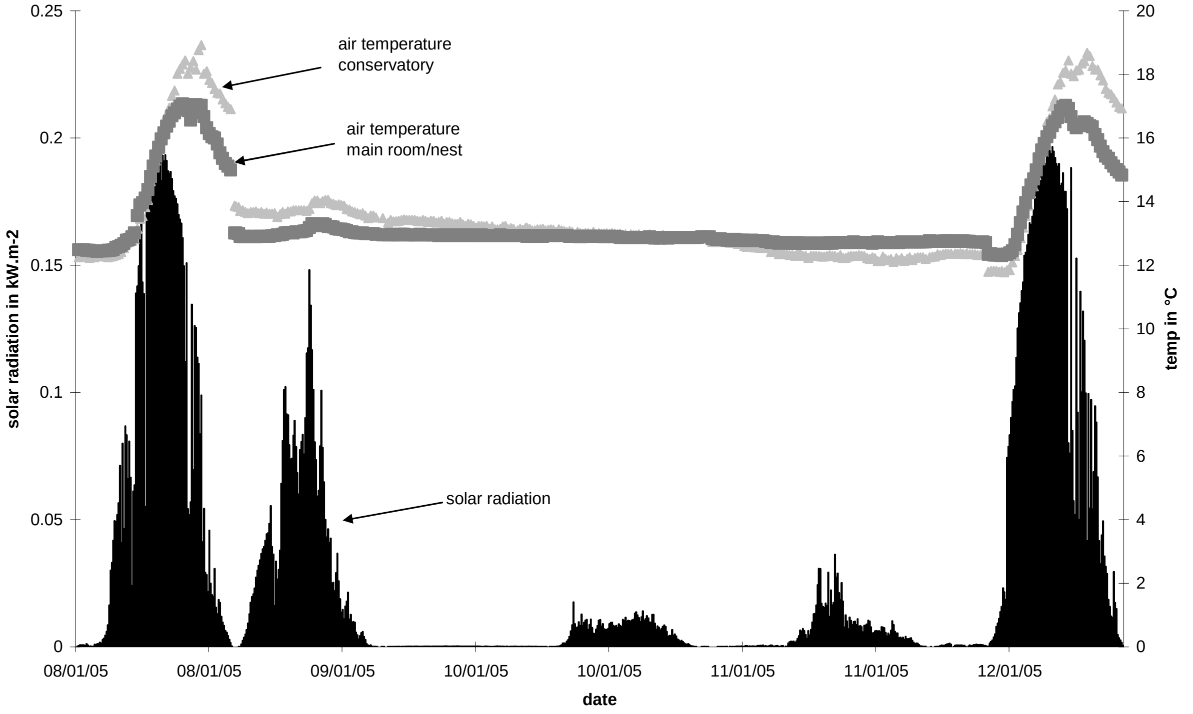


Figure 7 Measured data for global radiation and internal air temperature January 2005

4.0 Computer Simulation Using IESVE.

IES Virtual Environment Software was used to make some initial predictions of the thermal performance of the ‘Earthship’. IESVE is an integrated set of building performance simulation modules linked to a key 3D modelling interface. There were a number of assumptions which had to be made in order to represent the ‘Earthship’s’ innovative design within this proprietary package.

4.1 Construction Assumptions

The tyre wall was represented by the thermal properties of a layer of cement plaster on a thin layer of hard rubber, a thick layer of common earth and a second thin layer of hard rubber. The thermal mass behind the tyres was represented in the model by the consideration of a ‘soil room’ given a consistent temperature throughout its profile but adjusted within the modelling process to see the effect on resultant room temperatures.

For simplicity of modelling the hut module has been excluded from the analysis at this stage. It is an independent thermal element and therefore will be investigated separately.

The initial analysis has been carried out using default climate data within the software. These data are based on Gatwick airport, approximately 35km from the site.

4.2 Differing Earth Bank Temperatures

The thermal performance of the earth wall has been simulated using three varying ‘soil room’ temperatures behind the tyres themselves 0^oC, 10^oC and 15^oC, assuming 0.4 air changes per hour of ventilation and without any internal gains.

The figures summarised in Table 1 show the predicted effects of a changing base temperature in the ESRW of the nest module and its resulting effect on internal air temperature during a simulated December (external air temperatures constant in each simulation at the Gatwick dataset of 12.5°C maximum and 6.5°C minimum). There is a considerable difference between the profiles for the internal air temperatures, with the maximum and minimum increasing significantly as soil temperatures are increased.

Table 1 Results from simulation of internal air temperatures for different wall temperatures

	Earth sheltered rear wall (ESRW) temp.		
Simulation parameter	**0°C**	**10°C**	**15°C**
Air temp max	9°C	12.5°C	14.5°C
Air temp min	1°C	5°C	7°C
Range	*8°C*	*7.5°C*	*7.5°C*

4.3 Differing Ventilation Rates

Simulation was also undertaken to investigate the effect of differing ventilation rates on temperatures within the ‘Earthship’ in the peak heating season of August. These results are shown in Table 2. Results indicate that increasing the air infiltration rate from the adjacent conservatory and 'nest' modules reduces the extremes of air temperature experienced in the south facing conservatory, dissipating some heat into the 'nest' module, causing air temperatures to rise in this area. The external air infiltration rate was kept constant.

Table 2 Results from simulation of different air change rates

	Air changes per hour		
Simulation parameter	**0.5**	**3**	**5**
Conservatory air temp max (approx)	51°C	46°C	44°C
Conservatory air temp min (approx)	17°C	14°C	13°C
Range	*34°C*	*32°C*	*31°C*
‘Nest’ module air temp max (approx)	26.5°C	27°C	28°C
‘Nest’ module air temp min (approx)	15°C	13°C	12°C
Range	*11.5°C*	*14°C*	*16°C*
External air temperature max (approx)	29°C	29°C	29°C
External air temperature min (approx)	7°C	7°C	7°C
Range	*22°C*	*22°C*	*22°C*

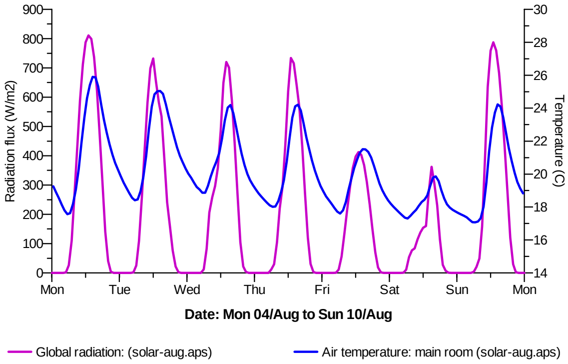
In this simulation, at whatever ventilation rate the room is considerably above thermal comfort levels for either the living room of a dwelling (22-23°C), or offices (21-23°C) (CIBSE 1999).

The study by Grindley & Hutchinson (1996) provides an interesting comparison with the initial modelling and measurement results being analysed from the Brighton project. Hutchinson & Grindley’s measured data was from Taos, the original climate for ‘Earthship’ design and the modelling scenarios were applied to this geographic along with a tentative model for the south east of the UK. These models also demonstrated overheating in both simulations for Taos, New Mexico and the south east UK. Importantly, it is noted that the main shading elements in ‘Earthship’ design are difficult to model in computer simulations (1996). ‘Earthships’ generally incorporate two large ‘planters’ (one in the conservatory, and one in the 'nest' module in which plants function primarily as grey and black water treatment cells). These provide adjustable shading with pruning (Reynolds 1990) along with blinds. Hutchinson & Grindley’s simulation was adapted to mimic the shading from planters and blinds by altering light levels and results were within +/- 1.2°C of the temperatures recorded in their measured data from an ‘Earthship’ in Taos, New Mexico. However, these recorded temperatures also exceeded thermal comfort (ranging between 24°C and 29°C).

The opportunity for comparison of modelled with measured data in the south east UK now exists. With monitoring data for a summer season not collected from the Brighton project at date of publication, and the lack of internal planters or shading devices in the unfinished building the future analysis planned on this long term monitoring project is certain to be of interest.

4.4 The Simulated Effect of Solar Radiation on Internal Temperature

Considering the intended south facing design of an ‘Earthship’ to deliberately attract solar gain it is unsurprising that the results shown in simulated weeks from both summer and winter months (Figures 8 and 9) demonstrate a close correlation between solar radiation and internal temperature. It is interesting that this correlation is even closer during the winter when the penetration of the winter sun is maximised by the angle of the glazing.



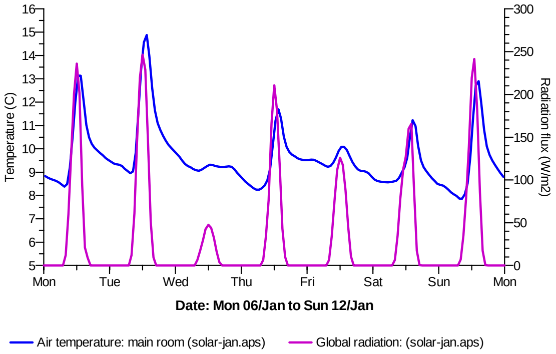


Figure 8 Global radiation and internal air temperature August (left)

Figure 9 Global radiation and internal air temperature January (right)

5.0 Discussion

Measured data over the same week of 08 January (as shown in Figure 9) is shown previously in Figure 7. This shows the same close correlation in peaks for both the conservatory and 'nest' module air temperatures. Unsurprisingly, the air temperature in the south facing conservatory responds more vigorously to the peaks in solar radiation. Future work on summer data will establish if this close correlation wanes when the angle of the suns penetration is more obstructed by the angle of the glass.

Comparing measured (Figure 7) and simulated results (Table 1) demonstrates that the maximum and minimum temperature ranges are comparable with that of the simulated data for the external air temperature (12.6°C maximum recorded, and -2.72°C minimum). However, the lower extremities were not reached in what has so far been generally considered as a fairly mild UK winter in 2004-5.

An average of the recorded maximum air temperatures in the conservatory and ‘nest’ module compared to the simulated mean temperatures (of the air mass in both rooms) makes an interesting comparison. At the maximum, the results are on average 5.6°C warmer in the Brighton ‘Earthship’ than the warmest of the simulations (influencing soil temperature of 15°C). At the minimum they are 3.36°C warmer in the Brighton project than in the simulation.

Figure 6 shows an average temperature of 14.81°C for the measured internal temperatures of the ESRW and to consider this in conjunction with the simulation with the nearest accuracy (‘soil room’ temperature at 15°C) it is unexplained why the internal air temperature in the measured data is higher. It therefore begs the question that the Brighton ‘Earthship’ is experiencing a contribution to internal air temperature not accounted for within the simulation. Reasons for this difference may become clear when data gathered over a longer period is analysed and tested against more detailed models.

The effect of the type of expected temperature gradation shown in Figure 6 has not been accounted for within the simulation at this stage into the research. It could be possible to create soil temperature zones within the representation of the ESRW by creating multiple ‘soil rooms’ with different properties as has been achieved in other simulations for earth-sheltered building (e.g. Littlewood & Geens 2001). However, it is intended to further analyse the behaviour of the ‘Earthship’ ESRW thermal mass with the use of specialist software such as Physibel to assess heat transfer within materials.

6.0 Conclusions & Future Work

The comparison between the modelled and measured data collected so far is showing overall that there is a general agreement between the sets of data on the movements and swings in the readings for the internal environment caused by the external conditions. However, the temperatures experienced within the Brighton 'Earthship' are consistently higher than that predicted by the model. At this stage it would be premature to assert the shading of the planters and blinds in the Brighton 'Earthship' would not be effective against summer overheating as they are not yet installed, so no comparison with measured data can be made. A number of gravity operated skylights under full occupant control (three in the 'nest' module of the Brighton 'Earthship') are also present, as potential regulators for overheating. The effect of these on any predicted or realised summer heating will need to be investigated when the building is occupied. However, it is suggested that some space heating is required in the winter months when the temperature is below that of the thermal comfort parameters as shown in Figure 5, which supports conclusions by Grindley and Hutchinson (1996).

Once the Brighton 'Earthship' is complete it will also be interesting to asses the thermal comfort experienced by occupants as it's intended final use as a flagship project combines plans for use as an office and also a seminar room, which have different comfort and design requirements than the traditional use of 'Earthships' for dwellings. During February 2005 new sensors have also been installed to measure the surface temperature of the tyre walls, the relative humidity of the interior rooms, and a black globe temperature sensor has been installed in the main/nest room to gather data on operative temperature. Along with extension to existing analysis with longer data collection periods, detailed simulation of the heat transfer of the thermally massive walls is planned using other mathematical modelling software.

References

Action Renewables, Technologies: Ground Source Heat Pumps. 2005. www.actionrenewables.org/techgshp.htm. Site visited 19-02-05

CIBSE (Chartered Institution of Building Services Engineers). 2001, Guide B2 Ventilation and Air Conditioning. CIBSE 2001

CIBSE. 1999, Guide A Environmental Design. CIBSE 1999

Department of Trade and Industry. February 2003, Our Energy Future, Creating a Low Carbon Economy. The Stationery Office.

Earthship Biotecture homepage. 2005 http://www.earthship.com/ . Site visited 19-02-05

Ecological Monitoring and Assessment Network (EMAN) Protocols and Standards (Canada). July 2001. Soil Temperature. www.eman-rese.ca/eman/ecotools/protocols/terrestrial/soil_temp/intro.html . Site visited 19-02-05.

Givoni, B. & Katz, L. 1985, Earth Temperatures and Underground Buildings. Energy and Buildings, 8, pp.15-25.

Goohew, S. & Griffiths, R. 2005, Sustainable Earth Walls to Meet the Building Regulations. Energy and Buildings, 37, pp. 451-459.

Grindley, P.C. & Hutchinson, M. 1996, The Thermal Behaviours of an Earthship. Renewable Energy, 8, Issues 1-4, May-August 1996, pp.154-159.

Harman, J. & Benjamin, V. April 2004, Foreword in Better Buildings Better Lives. Sustainable Buildings Task Group, Department of Trade and Industry (DTI).

Littlewood, J.R. & Geens, A.J. 2001, The Simulated Thermal Performance of a Pair of Two Storey Earth Sheltered Houses for the UK Climate. COBRA Conference Papers (the Construction Research Conference of the RICS Foundation) Kelly, J. & Hunter, K. (eds.)

Reardon, C. McGee, C. & Milne, G. 2005, Greenhouse, 'Thermal Mass' Simple Design Guide to Sustainable Design for Dwellings' http://www.greenhouse.gov.au/yourhome/technical/fs17.htm . Site visited 19-02-05

Reynolds, M. 1990, Earthship Volume 1: How to Build Your Own. Solar Survival Press, Taos, New Mexico.

Reynolds, M. 2000, Comfort In Any Climate. Solar Survival Press, Taos, New Mexico.

Silber, R. 1991, The Prospects of Earth Sheltered Development in the U.K. BSC (Hons) Building Engineering & Management Dissertation Submission. Brighton Polytechnic.